# Network structure, risk and strategic investments: An experimental analysis

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**Abstract**

This paper explores effects of network positions and individual risk attitudes on individuals' strategic decisions in an experiment when actions are strategic substitutes. The game theoretic basis for our experiment is the model of Bramoullé and Kranton (2005). We observe subjects' strategic investment decisions in five simple network structures. We find that the likelihood to specialize or to free ride is higher in asymmetric structures. Moreover, behavior is related to risk attitudes, but this influence is strongly affected by network parameters. Coordination fails in the dynamic setting and we do not observe any convergence of behavior to equilibrium.

*Keywords:* Social networks, experiment, coordination, strategic substitutes, risk aversion

*JEL classification:* C91, D00, D81, D85, C72, H41

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## 1 Introduction

The economics of social networks has gained increasing attention in the past decade, manifested in an explosion of game theoretical models on formation, stability and efficiency of networks and the "wide variety of settings where social networks play a role [still] leads to an almost endless set of interesting avenues to investigate" (Jackson 2005, p.59). As predictions from models continue to proliferate, we need to confront those with rigorous empirical tests in order to deduct a more general theory. "Experiments provide an important test bed for results which can be very difficult to pinpoint outside of the controlled environment of a laboratory" (Jackson 2005, p.60).

We conduct such a test for a network model presented by Bramoullé and Kranton (2006), in which individuals invest in the production of a local public good. Their paper provides the first analysis of a game played on a network when actions are strategic substitutes. It is motivated by Foster and Rosenzweig (1995) who find evidence of free riding in farmers' experimentations with a new technology: Farmers tend to experiment less when their neighbors experiment more. The model is characterized by two main features: agents are embedded in a fixed social network; and agents' payoffs are directly affected by their partners' actions. Most papers sharing these two assumptions look at positive social interactions and coordination games. In contrast, in their paper Bramoullé and Kranton (2006) study a game with features of an anti-coordination game, played on fixed networks and analyze the effects of network structure on individual behavior. Their analysis leads to three main insights. "First, social networks can lead to specialization. In any network there is an equilibrium where some individuals contribute to the public good and others completely rely on their efforts. In many, particularly asymmetric, networks this extreme form of free-riding is the only equilibrium outcome. In all networks, such patterns are the only stable outcomes. Hence, an agent's position in a network can determine whether or not they contribute to the public good. Second, specialization can have welfare benefits. It may benefit the society as a whole for some agents to specialize in public good contributions and others to rely on their results. This outcome arises when contributors are linked, collectively, to many people in society." (Bramoullé and Kranton (2006, p.2) A specific feature present in their model is the fact that all network structures support multiple equilibria, with the tendency that the denser and the more symmetric the structure the larger the number of equilibria. This adds a significant amount of *strategic uncertainty* to individual players. Related to the theory of global games as one of the more recent theoretical refinement concepts, we consider players' subjective beliefs about other players' actions.[1] For our purpose we link those to features of the network structure and show that the more transitive social links are the more is strategic investment influenced by individual risk attitudes. On the other hand, the more links a players has in his social network (the higher his degree), the lower his strategic uncertainty in our context. This indicates that there is an interesting as well as promising link of our research on social networks to recent theoretical and experimental studies on strategic uncertainty, as e.g. of Heineman, Nagel and Ockenfels (2004a) and (2004b).

We designed an experiment to test hypothesis derived from the model of Bramoullé and Kranton (2006) as well as from our considerations about risk attitudes and ran a first pilot with 30 subjects. First we test whether individual investment is characterized by more specialization in asymmetric network structures than in symmetric structures and we find strong support for this hypothesis. Second, we test whether welfare is higher in structures where in equilibrium there is a little specialization (in our examples this is the complete network) and find that in the experiment this is true. The explanation may be related to our third hypothesis: Based on our conjecture we hypothesize that next to the features of a specific network position also personal risk attitudes have an impact on strategic investment (the more risk averse the higher individuals' investment). Thus, we find that risk aversion leads to overinvestment. Theoretically we conjecture that the strategic uncertainty is lower the higher a player's degree, while it is higher the more transitive a player's relations. This relation seems to be supported in our experiment. Finally we test whether behavior converges towards equilibria with more specialization in repeated interaction. We do not find patterns of convergence of strategies in our setting.

We measure risk aversion by combining the experiment with a questionnaire containing Zuckerman's (1994) Sensation Seeking Scale V (SSS-V). Most personality theorists attribute differences in human behavior to the "traits" individuals or groups of people possess, and the amount of each trait possessed. The fundamental concept central to most trait theories is that traits are life-long and relatively consistent. According to Allport

[1] See Carlsson and van Damme (1993) and Morris and Shin (2000) as well as Harrison (2003) and Hellwig (2002).

(1961), traits (sensation seeking, achievement seeking, sensuousness, etc.) are "neuropsychic structures having the capacity to render many stimuli functionally equivalent, and do initiate and guide equivalent forms of adaptive and expressive behavior" (1961, p. 347.) Traits therefore account for consistency in human behavior patterns. Since sensation seekingness is positively related to individual risk attitudes we included this well validated questionnaire.[2] We find that our sample scores less on all dimensions than the normative sample except for the experience seeking dimension.

While theoretical research on economic networks has received extensive interest in the past 10 years, experimental work on networks in economics has been neglected until very recently.[3] Seminal work by Kandori, Mailath, and Rob (1993) and Young (1993) has triggered intense interest in the question of equilibrium selection in coordination games. Important research examines the impact of different network structures on equilibrium selection and whether players will form networks that lead to play of the efficient Nash equilibrium in the coordination game if players can choose their network partners themselves.[4] Extensive literature exists on experiments on coordination games.[5] Keser, Ehrhart, and Berninghaus (1998, 2002) present the first experiments that considers the role of networks in coordination games. In one treatment players are located on a circle, while they are located on a two-dimensional lattice in the second treatment. While the size of a player's neighborhood remains constant across treatments , the neighborhood structure differs. The authors find that play is more likely to converge to the risk-dominant equilibrium when players interact on the lattice than on the circle. This result is rather striking since subjects were not informed about the precise neighborhood structure of the population in the two treatments. The authors conjecture that subjects observe individual play to be more changing in the lattice treatment than in the circle treatment and that therefore risk dominance as an individual motive has more power in the lattice treatment than in the circle treatment. In line with our results, this

[2]See Harrison et al. (2006) for a systematic review of instruments that measure risk propensity.

[3]See Kosfeld (2004) for an interesting survey on experimental contributions in that field.

[4]Ellison (1993) and Morris (2000) analyze the role of local interaction networks in the spread of particular strategies simple coordination games, showing how play converges to the risk-dominant equilibrium if players are located on a circle and interact with their two nearest neighbors. Blume (1993) and Kosfeld (2002) prove convergence to the risk-dominant equilibrium in a population of players located on a d-dimensional lattice.

[5]See Ochs, 1995 for a review.

finding suggests that it is less an individual player's degree but also other network features that (even indirectly) influence individual behavior.

Boun My, Willinger, and Ziegelmeyer (2001) also analyze the effect of interaction networks on equilibrium selection. Using a setting similar to Keser et al. (1998), they compare the repeated play of a 2×2 coordination game under global and under local interaction with varied degrees of risk dominance of the inefficient equilibrium. In their setting the interaction structure itself does not seem to play a significant role in the convergence of play. In particular, contrary to the studies described above, Boun My et al. do not find that players who interact locally on the circle coordinate more frequently on the risk-dominant equilibrium.

The recent wave in experimental economics focusing on social and economic networks emphasizes individual incentives for network formation, as well as the impact of networks on equilibrium selection, competition, and cooperation. Results of the experiments so far have shown that network configurations have important effects on economic outcomes, such as the convergence towards equilibria, the support of Pareto superior states, or the distribution of surplus among economic agents. We contribute to this research by focussing on the effect of network configurations on individual investment decisions in games with strategic substitutes.

The paper is structured as follows: In the next section we present the theoretical foundation for the hypotheses that we aim to test in the experiment. In Section 3 we present the experimental design, in Section 4 the results and we conclude in Section 5.

## 2 A game of strategic investment in networks

In this section we briefly summarize the model of Bramoullé and Kranton (2006). Suppose there is a set of agents $N = \{1, ..., n\}$ and let $e_i \in \mathbb{R}^+$ denote agent $i$'s level of effort spend on know-how production. Agents are arranged in a network which is represented by an undirected network $g$, that is: $g_{ij} \in \{0, 1\}, g_{ij} = g_{ji}$, for all $j \in N$, which implies that know-how flows both ways. Hence, if $g_{ij} = 1$, agent $j$ benefits directly from agent $i$'s produced know-how. Since agent $i$ knows his own know-how, $g_{ii} = 1$. Let $N_i = \{j \in N \backslash i : g_{ij} = 1\}$ denote the neighbors of agent $i$ that benefit directly from $i$'s effort. Each agent receives a benefit from producing know-how $u_i(e_i, ..., e_n; g) = b(e_i + \sum_{j \in N_i} e_j)$ with $b(0) = 0$ and $b' > 0$ and $b'' < 0$.

Marginal costs of producing know-how are constant and equal to $c$. Let $e^*$ denote the know-how production level at which to an individual agent, marginal costs are equal to marginal benefits. It is straightforward to show that:

**Proposition 1** *(Bramoullé and Kranton (2006)) A profile* $\mathsf{e}$ *is a Nash equilibrium if and only if for each agent* $i$ *either (1)* $\sum_{j \in N_i} e_j \geq e^*$ *and* $e_i = 0$ *or (2)* $\sum_{j \in N_i} e_j \leq e^*$ *and* $e_i = e^* - \sum_{j \in N_i} e_j$.

Obviously, levels of know-how production are strategic substitutes; the more one agent produces the less produce his direct neighbors. In general, the equilibrium distribution of know-how production will vary between two extremes: either a profile $\mathsf{e}$ is such that for all agents $i$ either $e_i = 0$ or $e_i = e^*$. This will be called a *specialized* profile. The other extreme is that all agents $i$ produce some know-how such that $0 < e_i < e^*$. This will be called a *distributed* profile. For our analysis two more results of Bramoullé and Kranton (2005) are of direct interest:

**Proposition 2** *(Bramoullé and Kranton (2006)) (i) For any structure* $\mathsf{g}$*, there exists a profile* $\mathsf{e}$ *that constitutes a Nash equilibrium, and for any structure* $\mathsf{g}$*, there exists a specialized profile* $\mathsf{e}$ *that constitutes a Nash equilibrium. (ii) An equilibrium is stable if and only if it is specialized and every non specialist is connected to (at least) two specialists.*

For a welfare comparison of different equilibria Bramoullé and Kranton take a second-best approach. We can express the welfare of an equilibrium profile $\mathsf{e}$ as the sum of the payoffs of the agents:

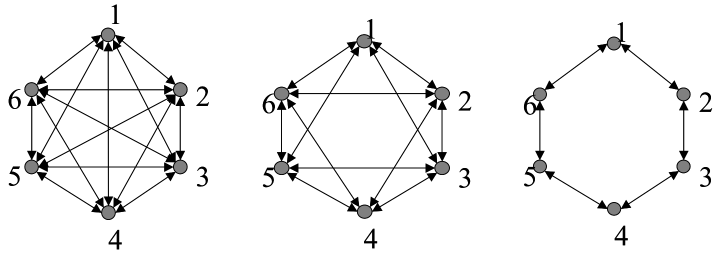
$$W(\mathsf{e}, \mathsf{g}) = \sum_{i \in N} b(e_i + \sum_{j \in N_i} e_j) - c \sum_{i \in N} e_i.$$

For a general welfare comparison across equilibria we thus need to measure the value of know-how above $e^*$.

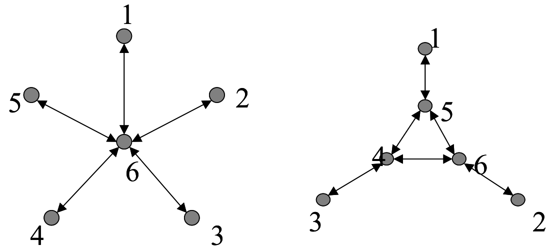
Now let us turn to some specific network structures and analyze them in some more detail. Throughout this paper we will set $N = 6$ and use the following benefit function from profile $e$ in graph $g$:

$$u_i(e, g) = a \ln(1 + e_i + \sum_{j \in N_i} e_j) - ce_i \tag{1}$$

with $a = 7,5$ and $c = \frac{1}{2}a$. This implies that $e^* = 1$ and that in equilibrium $e_i = \max\{0, 1 - \sum_{j \in N_i} e_j\}$. Now consider the following examples of network structures:




Complete (1), overlapping neighbors (2), circle (3)




Star (4), core-periphery (5)

For each of these network structures we can characterize the full set of Nash equilibria:

- Consider the *completely connected network* (1) with $N = 6$ and $e^* = 1$. Any profile such that $\sum_{i \in N} e_i = 1$ constitutes an equilibrium.

- Consider the *overlapping neighbors network* (2) with $N = 6$ and $e^* = 1$. The following strategy profiles constitute Nash equilibria: (i) $(\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5})$, and (ii) $(0, 0, 1, 0, 0, 1)$.

- Consider the *circle network* (3) with $N = 6$ and $e^* = 1$. The following strategy profiles constitute Nash equilibria: (i) $(1, 0, 1, 0, 1, 0)$, (ii) $(0, e, 1-e, 0, e, 1-e)$ and (iii) $(e, 1-2e, e, e, 1-2e, e)$ or (iv) symmetric hybrids of the last two.

- Consider the *star network* (4) with $N = 6$ and $e^* = 1$. There are only two types of Nash equilibria: Either the center is a specialist and the agents in the periphery do not invest, or the agents in the periphery are specialists and the center does not invest.

- Consider the *core-periphery network* (5) with $N = 6$ and $e^* = 1$. There are only two types of Nash equilibria: Either no core agent is a specialist and the agents in the periphery do invest $e^* = 1$, or one core agents is a specialist and invests $e^* = 1$ and all his neighbors do not invest, and all the remaining periphery agents are specialists and invest each $e^* = 1$.

From those examples we can now derive some more specific results. First of all we need to distinguish between symmetric and asymmetric networks. In symmetric network structures all players $i$ have the same number of links to other players (degree). In asymmetric network structures is the distribution of links between players concentrated. Comparing the set of equilibria for those two different classes of networks we can state the following:

**Proposition 3** *With $N = 6$ and a benefit function (1), specialized strategy profiles constitute the only Nash equilibria in the star and the core-periphery network, while also distributed profiles constitute Nash equilibria in the symmetric (full, overlapping neighbors and circle) networks.*

If we compare the welfare for various equilibria in the different network structures, it is easy to show that the networks can be ranked according to the welfare they generate. The welfare generated is higher the more players benefit from know-how that is produced above the equilibrium level. If we calculate the welfare of each profile for any network and take the average over all equilibria per network structure, we can conclude the following:

**Proposition 4** *With $N = 6$ and a benefit function (1), on average in equilibrium, the complete network generates the highest welfare. The circle and the overlapping neighbors rank second and third, respectively. The star generates the second lowest welfare and the core-periphery network ranks last.*

As there are multiple equilibria for all network structures agents will be confronted with *strategic uncertainty* because they cannot assign probabilities to any outcome by relying only on deductive reasoning. All outcomes are consistent with optimizing behavior and rational expectations so that neoclassical theory cannot help to predict behavior.

Theoretical refinement concepts are based on assumptions on players' beliefs about other players' behavior. One such concept is the theory of global games proposed by Carlsson and van Damme (1993). The theory starts from an environment of incomplete information about economic fundamentals.

In a global game setting, there is a unique equilibrium where each player chooses the action that is a best response to a uniform belief over the proportion of his opponents choosing each action. Thus, when faced with some information about the underlying state of the world, each player hypothesizes that the proportion of other players who will opt for a particular action is a random variable that is uniformly distributed over the unit interval and choose the best action under these circumstances. This approach, further advanced by Morris and Shin (2002), generates predictions for games with strategic complementarities (in which equilibria can be ranked), and Harrison (2003) developed it further for games with strategic substitutabilities in which players can be ranked. Hellwig (2002) finds that the global game solution for games with strategic complementarities can be approached by uncertainty about other players' risk aversion. There is to the best of our knowledge no such theory that characterizes a global game solution for anti-coordination games on networks as the one we are interested in.

In what follows we make an attempt to use ideas from the above mentioned approaches and link individual investment in the above described network games to a player's position in a network and his degree of risk aversion. Suppose first that we can characterize a player $i's$ utility from the investment into know-how by his *constant degree of risk aversion* $r_i$, such that:

$$U(e_i, g, r_i) = \frac{a\ln(1 + e_i + \sum_{j\in N_i} e_j)^{1-r_i}}{1 - r_i} - ce_i$$

Suppose for simplicity that each player has a binary decision to either invest as a specialist or to be a free rider, i.e., $e_i \in \{0, 1\}, \forall i \in N$. Define a belief $p$ that a randomly selected neighbor $j$ of player $i$ in network $g$ is investing as a specialist (hence, $e_j = 1$). A player $i$ with degree of risk aversion $r_i$ will find it optimal to play 1, whenever he believes that no other player will play 0 with a probability at least as large as $(1 - p)$, and he will prefer 0, whenever his belief that other player plays 0 falls below $(1 - p)$. Player $i$'s expected utility from investing is larger than from not investing if:

$$\begin{aligned} & (1-p)^{N_i}\frac{(a\ln(1+1))^{1-r_i}}{1-r_i} + (1-(1-p)^{N_i})\frac{(a\ln(1+1+1))^{1-r_i}}{1-r_i} - c \\ = & \ (1-(1-p)^{N_i})\frac{(a\ln(1+1))^{1-r_i}}{1-r_i} \end{aligned}$$

Define $p(N_i, r_i)$ as the solution to this equation. For given values of $N_i$ we find that $p(N_i, r_i)$ is increasing in $r_i$; hence, the more risk averse a player is the higher has to be his belief that the other players play 1, in order to induce him to play risky, $e_i = 0$.[6] And the higher his ex post expected return to playing 0, the lower the threshold probability at which $e_i = 0$ becomes optimal. Moreover, for given values of $r_i$, the probability $p(N_i, r_i)$ is decreasing in $N_i$. Thus, the higher a player $i$'s degree, the lower has to be his belief that the other players play 1, in order to induce him to play risky, $e_i = 0$. These arguments lead us to the following conjecture:

**Proposition 5** *The more risk averse a player, the more does he invest. A high degree will counterbalance this effect and reduce a player's incentives to invest.*

The experiment which will be described in the following section was designed to test the predictive power of the propositions and the conjecture outlined in this section.

# 3 Design of the Experiment

Sessions were run at the experimental laboratory ELSE at Utrecht University in December 2005. For this pilot master students from the programmes "International Economics and Business" and "Economics and Law" were asked to participate, but participation was not part of a course. The procedure during the two sessions was kept the same and both sessions were computerized, using a program written with z-tree (Fischbacher, 1999). 30 Students participated and were seated in a random order at PCs. Instructions (see Appendix A1) were then read aloud and questions were answered in private. Throughout the sessions students were not allowed to communicate and could not see others' screens. Subjects were randomly assigned to groups of size N=6. There were three groups in the first session and two in the second, and subjects did not know who the other members of their group were. Before starting the experiment, subjects had to answer a few questions concerning their understanding of the rules. The experiment started, when all subjects gave the correct answers to these questions.

[6] For the case $N_i = 2$ it is easliy checked that this is true for any value of $r_i$. Other comparative static properties can be checked in the numerical simulations that are available upon request.

In the experiment, subjects first faced 5 blocks of 4 independent decision situations. In each situation subjects decided on how much to invest, with investments being any positive number with two decimals in the interval [0,1]. Investment gave a payoff that ranged from € 0 to € 13,44 (see Appendix A2). In each block all subjects were in a different network and in each situation each subject was in a different network position, such that a sequence of 4 one-shot games for each given network structure is played (see the previous section for the network structures we used). In a second treatment subjects then face 2 blocks of 7 decision situations. While subjects' decisions remained the same, the only difference to the first treatment is that now subjects play in fixed groups and on the same network position for each of the 7 situations such that a repeated game is played for 7 rounds. In both treatments all investment decisions as well as all payoffs were revealed after each decision to all subjects belonging to the same network and were thus common knowledge.

Afterwards, each player had to answer a questionnaire asking for personal data, and the Zuckerman Sensation Seeking Scale V (SSS-V). The duration of the experiment was 45 to 60 minutes with an average payoff of € 10.90 per subject. Subjects received 5€ show-up fee and 3 out of the 34 periods were randomly chosen to determine the actual payment in Euros. Actual payment was the average payoff of these three periods. This lead to minimum earnings of €1.20 and maximum earnings of €9.90.

The chosen design has been motivated by several considerations: In the first treatment we use a one-shot game to identify the relation between individual decision and risk aversion of players in a given network position. Any kind of interaction effects within specific dyads could so be avoided. We played each network four times to generate a sufficient amount of observations for each network structure and each network position. In the second treatment we use a repeated game to observe dynamic interaction and allow for convergence of strategies. We select a single situation for payments to reduce incentives to "experiment" and to give us the highest possible impact of risk aversion on any decision. Two high-stake sessions in Heinemann, Nagel and Ockenfels (2004) indicate that paying a randomly selected situation does indeed evoke risk-averse behavior in coordination games.

The data on subjects' risk attitudes were gathered via a written survey using 40 forced choice items. The instrument used was an adaptation of the instrument developed in 1979 by Zuckerman with a high reported internal reliability coefficient (Cronbach's alpha reliability coefficients ranges from .85 to .90 for all scales). This instrument assesses the respondents' sensation seeking or risk taking behavior on four subscales; experience seeking (ES), thrill and adventure seeking (TAS), disinhibition (DIS), and boredom susceptibility (BS). The Sensation Seeking Scale currently is the most widely used form of the sensation seeking scale with the largest volume of normative data supporting it (Zuckerman, 1994). The normative sample (age range of 17-23 years) for the SSS-V consisted of 410 male and 807 female undergraduate students from the University of Delaware (Zuckerman, 1994).

The subscales have a score range of 0-10 points, with 10 being high. The total scale score is the sum of the subscales scores. The thrill and adventure seeking subscale examines the respondents' appeal to activities of physical danger or risk taking; the normative score for men (women) is 7.7 (6.6) on this subscale. In the experience seeking subscale desires for new experiences are assessed. Subscale items include the desire for exotic travel or association with unusual friends; the normative score for men (women) is 5.0 (5.2) on this subscale. Items in the disinhibition subscale examine respondents' desire to exhibit uninhibited/unrestrained behaviors. These include behaviors considered high risk such as; heavy drinking, drug use, or having a variety of sexual partners; the normative score for men (women) is 6.2 (5.5) on this subscale. The final subscale, boredom susceptibility, assesses an individual's dislike of repetitive experiences or predictable experiences; the normative score for men (women) is 3.7 (3.2) on this subscale.

## 4 Results

We conducted the pilot experiment with 30 students from Utrecht University, 30% of the subjects were foreigners, 80% men and the average age was 22,5 years. How our sample scored in comparison with the normative sample (adjusted to the same ratio of women and men as our sample) can be seen in the following table:

| | sample | norm. |
|---|---|---|
| TAS | 6.7 | 7.5 |
| ES | 5.6 | 5.0 |
| BS | 3.3 | 3.6 |
| DIS | 5.3 | 6.1 |

Table 1: SSS-V scores

Hence, our sample seemed to be somewhat less sensation seeking than the normative sample from 1994, an observation that we do not question at this point. A first comparison of average investment in the five networks reveals that investment levels are significantly different under the different network structures. In Table 2 can be seen that mean investment as well as standard deviation is highest in the star network and lowest in the complete network and that the two are significantly different at the 1% level (using two-tailed ). Also in the overlapping neighbors structure and the circle structure mean investment is significantly lower than in any of the two asymmetric structures.

| **Investment** | | **Star** | **Core-periphery** |
|---|---|---|---|
| **Complete** | mean | *0.218*****; 0.652**** | *0.218*****; 0.455**** |
| | stdv | 0.306***; 0.420*** | 0.306***; 0.437*** |
| **Overlapping** | mean | *0.223*****; 0.652**** | *0.223*****; 0.455**** |
| | stdv | 0.320***; 0.420*** | 0.320***; 0.437*** |
| **Circle** | mean | *0.349*****; 0.652**** | *0.349****; 0.455*** |
| | stdv | 0.372*; 0.420* | 0.372**; 0.437** |
| **Core-periphery** | mean | *0.455*****; 0.652**** | |
| | stdv | 0.437; 0.420 | |

Table 2: Two sample t tests (paired) of mean investment and variance ratio test for standard deviations per network (*significant at 10%, **significant at 5%, *** significant at 1%). Each network structure has $n = 120$ observations.

This is a first indication that network structure matters for individual investment decisions. In the following we will analyze investment behavior in more detail along the predictions of the theoretical model.

## 4.1 Specialization and network structure

Proposition 3 predicts that investment levels in asymmetric structures are $e_i \in \{0, 1\}$. As we can see from subjects' investment decisions in Appendix A3, which reports the frequencies of investment levels for the five networks, not all observed investments are so extreme. In fact, in both asymmetric structures we also observe intermediate investment values. Thus, to test this prediction we first compute the percentage, in which subjects chose investments of either 0 or 1 (out of all respective decisions) per network structure. As can be seen in Table 3, 70% of investments decisions in the star network are either 0 or 1, while this applies only to 52% of decisions in the complete network.

| Network | % of decisions with $e_i \in \{0, 1\}$ |
|---|---|
| Complete | 52 |
| Overlapping neighbors | 60 |
| Circle | 54 |
| Star | 70 |
| Core-periphery | 62 |

Table 3: Percentage of "extreme" decisions per network

To be able to control for other influences in the testing of Proposition 3 we estimate a probit model, which includes other potential determinants of extreme investment behavior. In particular, we specify the degree of the network position (degr), as well as subjects' age (age), gender (sex0f1m) and a dummy variable for non-dutch nationality (dnat) as other possible explanatory variables. Furthermore, we include an 'experience' variable reflecting the number of times subjects have been in the same one-shot situation (Period2) to control for possible learning effects.

The models 1 to 3 in Table 4 test the influence of asymmetric network structures on the probability of choosing an extreme value of either 0 or 1. As we can see this probability is increasing significantly if subjects are in a star network, represented by a dummy variable 'dstar'. Since the sample includes all observations, the coefficient of the dummy must be interpreted in relation to the symmetric network structures. We also find a positive influence of the dummy for the core-periphery network (dcore), but only at a10% level and only if we control for age. This last results needs to be validated in a larger sample as it rather difficult to explain and might depend on age-related outliers. In Model 3 also the 'experience' variable Period2 has a significant positive effect on investment ($p < 0.1$), pointing at the fact that although playing one-shot games, subjects needed some time to understand the network structure and the network effects. Model 4 to 6 analyze the symmetric network structures and we find that the likelihood to choose either 1 or 0 is decreasing if the game is played in any of the symmetric structures. Furthermore, a player's degree has a positive effect in the symmetric but not in the asymmetric networks. This might indicate that the more connected a player, the more likely he free rides. We will come back to that result under Subsection 4.3. In general, we infer from these results that Proposition 3 has sufficient predictive power to explain differing investment tendencies in symmetric vs. asymmetric network structures.

| | Dependent variable: Probability of specialization or freeriding | | | | | |
|---|---|---|---|---|---|---|
| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
| Period2 | 0.02931 | 0.02948 | 0.03016* | 0.02913 | 0.02949 | 0.03028* |
| | (1.63) | (1.64) | (1.66) | (1.62) | (1.63) | (1.66) |
| dstar | 0.15199*** | 0.18619*** | 0.19640*** | | | |
| | (2.98) | (3.14) | (3.29) | | | |
| dcore | 0.06038 | 0.09108 | 0.09799* | | | |
| | (1.18) | (1.59) | (1.69) | | | |
| degr | | 0.01898 | 0.02216 | | 0.04455* | 0.05434** |
| | | (1.17) | (1.35) | | (1.68) | (2.01) |
| dfull | | | | -0.14079** | -0.28441*** | -0.31911*** |
| | | | | (2.52) | (2.76) | (3.05) |
| dcircle | | | | -0.12432** | -0.13399** | -0.13997** |
| | | | | (2.23) | (2.38) | (2.46) |
| dneighbors | | | | -0.06617 | -0.16686** | -0.19221** |
| | | | | (1.19) | (2.03) | (2.29) |
| sex0f1m | | | 0.06106 | | | 0.05879 |
| | | | (1.02) | | | (0.98) |
| age | | | -0.04450*** | | | -0.04540*** |
| | | | (2.88) | | | (2.93) |
| dnat | | | -0.00614 | | | -0.00686 |
| | | | (0.10) | | | (0.11) |
| Observatior | 600 | 600 | 600 | 600 | 600 | 600 |
| Absolute value of z statistics in parentheses | | | | | | |
| * significant at 10%; ** significant at 5%; *** significant at 1% | | | | | | |

Table 4: Determinants of specialization and free riding

## 4.2 Efficiency of network structures

Based on Proposition 4 we test whether we observe the predicted ranking of networks according to generated total profits (corresponding to total welfare in this setting). As a measure we take the mean profit and find that the star generates the lowest profit while the complete network generates the highest profit and that the two are significantly different. As expected is the variance of profits highest for the star. A reason may be that miscoordination leads to zero profits in the star for the players in the periphery, while it leads to positive profits in the complete network as well as in the overlapping neighbors network. The number of neighbors might explain why the overlapping neighbors network generates the second highest welfare.

| Profit | | Star | Core-periphery |
|---|---|---|---|
| **Complete** | mean | *4.89****; *3.37**** | *4.89****; *3.57**** |
| | stdv | 2.63***; 3.69*** | 2.63; 2.37 |
| **Overlapping** | mean | *4.38***; *3.37*** | *4.38****; *3.57**** |
| | stdv | 2.31***; 3.69*** | 2.31; 2.37 |
| **Circle** | mean | *3.72; 3.37* | *3.72; 3.57* |
| | stdv | 2.07***; 3.69**** | 2.07; 2.37 |
| **Core-periphery** | mean | *3.57; 3.37* | |
| | stdv | 2.37***; 3.69*** | |

Table 5: Two sample t tests (paired) of mean profit and variance ratio test for standard deviations per network (*significant at 10%, **significant at 5%, *** significant at 1%). Each network structure has $n = 120$ observations.

The same problem of miscoordination is present in the circle as well as in the core-periphery network which might explain why those do not generate significantly different levels of welfare compared to the star network, as can be seen in Table 5. In conclusion, we can thus reject the predictions based on Proposition 4.

### 4.3 Specialization and individual risk attitudes

Conjecture 5 implies that due to strategic uncertainty, risk attitudes influence individual investment decisions. The prediction is that individuals invest less, the less risk averse (the more sensation seeking) they are. On the other hand, strategic uncertainty motivates risk averse players to specialize. Furthermore, the conjecture implies that the more players' relations are transitive, the higher the investment, and on the other hand, the higher a player's degree, the lower his investment. To test this conjecture, we include the subjects' sensation seeking parameter as well as the degree of their position in the network in an OLS regression to estimate possible effects on their investment level. We then run this regression for each network individually in order to isolate individual effects from other structural effects (e.g. level of transitivity in networks). Since the degree is identical for all positions in symmetric networks, this variable can only be tested in asymmetric settings. Table 6 reports the results.

| | Dependent variable: Individual investment level | | | | |
|---|---|---|---|---|---|
| | Complete | Star | Core-Periphery | Circle | Overlapping neighbors |
| sssv(TAS) | -0,00741 | -0,0189 | -0,0009 | -0.04215** | -0.04442*** |
| | (0.51) | (1.12) | (0.05) | (2.47) | (3.24) |
| Period2 | -0.04393* | 0.09807*** | 0,01323 | -0.05307* | 0,02853 |
| | (1.77) | (3.4) | (0.47) | (1.81) | (1.21) |
| degr | | -0.12264*** | -0.27148*** | | |
| | | (5.46) | (8.53) | | |
| sex0f1m | 0,05958 | 0,10004 | -0.18181* | 0,06224 | 0,02971 |
| | (0.71) | (1.02) | (1.92) | (0.63) | (0.37) |
| age | -0,01052 | -0,02516 | 0.05877** | 0,04079 | 0.06829*** |
| | (0.5) | (1.03) | (2.47) | (1.65) | (3.44) |
| dnat | 0,12085 | -0,07849 | -0,1376 | -0,13999 | -0,08394 |
| | (1.39) | (0.77) | (1.38) | (1.36) | (1.02) |
| Observations | 120 | 120 | 120 | 120 | 120 |
| R-squared | 0,05 | 0,33 | 0,41 | 0,11 | 0,22 |
| Absolute value of t statistics in parentheses | | | | | |
| * significant at 10%; ** significant at 5%; *** significant at 1% | | | | | |

Table 6: Individual investment and risk attitude

Looking first at the complete network in Table 6, investment decisions do not seem to determined by the risk attitude of the subjects, nor by other control variables like age, nationality, or gender. The 'experience' variable (Period2) shows a statistically significant coefficient (with a moderate t value of 1.77; $p < 0.1$) which indicates that individuals start with high investments and learn to reduce their input the more often they play the one-shot game in the same network structure. Overall, the model can explain only 5% of the total variation in investment levels, conveying the impression that subjects' decisions contain a considerable amount of noise or randomness.

In the star network, players' degree has the expected negative effect (the center player invests significantly less than the non-center players). The inclusion of degree as an additional explanatory variable also leads to a much higher R-square of 33%. As in the complete network, risk attitudes do not play an important role and individuals seem to learn. Interestingly, the 'experience' variable (Period2) is now positively correlated with the level of investment. This indicates that the players in the periphery start with low investments and increase their input as a response to zero (or low) profits in previous games.

The results for the core-periphery network are comparable to the star, but learning appears to be more difficult, possibly due to the fact that the asymmetry of the network is more complicated and not focused on a single (central) player anymore. Furthermore, the control variables gender and age additionally explain some variation. As a robustness check we omitted the control variables in all network regressions. The results do not change qualitatively.

In line with our conjecture, risk attitudes play a significant role in the circle and in the overlapping neighbors network. The higher the score in tension and adventure seeking (TAS) the more risk loving subjects are and the more they free ride.[7] In fact, on average, a one point increase on the TAS scale lowers the investment level in each of the two networks by more than 4%. As in the complete network, players' degree is constant (by construction of symmetric networks) and can not be used to explain variation in investment.

Altogether we can conclude that if variables are statistically significant, the sign of their coefficients correspond to the predictions of our conjecture. This specifically applies to a subject's degree, which clearly shows the hypothesized negative effect. The influence of risk, although generally reporting the expected signs, is only significant in the circle and overlapping neighborhoods network. Also, a comparison between networks with regard to low or high transitivity (e.g. star/ring vs. complete/overlapping neighbors) does not allow firm conclusions since, both, networks with low and with high transitivity report significant (e.g. circle/overlapping neighbors) as well as insignificant effects (e.g. complete network/star) of risk attitudes. Although this indicates some support for the hypothesized notion of compensating effects between transitivity and degree in combination with risk, we need more detailed analysis and further studies with more general networks to better understand the joint effects of these and other network characteristics.

### 4.4 Stability of equilibria

Proposition 2 predicts that in the core-periphery network the equilibrium in which all the core players free ride and all the periphery players specialize is the unique stable equilibrium. Whether players converge to this equilibrium was tested in the second treatment in which subjects were in fixed network

[7] Also some of the other sensation seeking dimensions as well as the average of all four dimensions lead to qualitative similar results.

positions and fixed groups for seven rounds. For our statistical test we divided the sample into two groups: core players (roles 4, 5 and 6) and periphery players (roles 1, 2 and 3).[8] We then tested with two separate probit specifications, whether the likelihood that core players choose an investment level of 1 or that periphery players choose a level of 0 is increasing with the rounds the game is played. Table 7 presents our findings.

| | Periphery players with 'specialist' investment = 1 (dependent variable) | | Core players with 'free rider' investment = 0 (dependent variable) | |
|---|---|---|---|---|
| | Model a | Model b | Model a | Model b |
| Period1 | -0.06610*** | -0.06655*** | 0.02938 | 0.03166 |
| | (2.61) | (2.62) | (1.14) | (1.21) |
| sssv(TAS) | -0.05037 | | 0.14803*** | |
| | (1.40) | | (3.82) | |
| sssv(avg) | | -0.06548* | | 0.21260*** |
| | | (1.94) | | (3.81) |
| age | -0.08804 | -0.03769 | -0.14277** | -0.22202*** |
| | (1.49) | (0.84) | (2.33) | (3.00) |
| sex0f1m | 0.41794 | 0.21567 | 0.24100** | 0.18163 |
| | (1.27) | (0.76) | (1.97) | (1.39) |
| dnat | 0.15271 | -0.10451 | -0.04241 | 0.10416 |
| | (0.49) | (0.39) | (0.20) | (0.44) |
| Observations | 105 | 105 | 105 | 105 |
| Absolute value of z statistics in parentheses | | | | |
| * significant at 10%; ** significant at 5%; *** significant at 1% | | | | |

Table 7: Convergence of strategies for core and periphery players respectively

For the periphery players we find a significant impact of the 'experience' variable Period1, which is role specific. The statistical significance of Period1 is expected, but, contrary to our prediction and also to the empirical findings in connection with the star (see Table 6), the likelihood that periphery players specialize decreases as the game is played more often. For the core players, Period1 shows an opposite but non-significant correlation with their level of investment. This indicates that, as in the complete network (see

[8] The results of the circle network structure in this repeated setting do not show any significant results.

Table 6), core players invest at a high level, but, in contrast to the complete network, they do not lower their investment, while the periphery does.

In line with our findings from the previous subsection, we also observe that the more players are risk loving, the more they free ride. However this applies mostly to core players, while the impact of risk attitudes on periphery players' investment is much smaller and also less significant (for the average of all sensation seeking dimensions, sssv(avg)) or not significant at all (sssv(TAS)). As age seems to be negatively correlated with sensation seekingness, (positively correlated with risk aversion) the result for this variable complements our previous findings. Robustness checks without the inclusion of age do not change the results qualitatively. In summary, although we detect some convergence on the side of the periphery players, we do not find any evidence for convergence towards the theoretically predicted stable network equilibrium in this experiment. Furthermore, the results offer additional support for the positive relation between risk aversion and investment levels (as predicted in Conjecture 5).

# 5 Concluding remarks

This paper explores the effects of network positions as well as individual risk attitudes on individuals' strategic decisions in an experiment when actions are strategic substitutes. The game theoretic basis for our experiment is the model of Bramoullé and Kranton (2005). We observed subjects' strategic investment decisions in five simple network structures in the laboratory. Our first hypothesis was derived from the theoretical prediction that investment levels in asymmetric structures are extreme in the sense that some players specialize while others free ride. We observe that not all subjects' investment decisions are so extreme. In fact, in both asymmetric structures that we analyze, we also observe intermediate investment values. Nevertheless, we find that individual behavior is determined by network characteristics. The likelihood to specialize or to free ride is significantly higher in asymmetric structures. More strikingly, we find that behavior is also related to risk aversion and experience seekingness, but that the influence is strongly affected by network parameters. This indicates an interesting aspect for future research: the interrelation of individual risk attitudes (that we measured using the SSS-V questionnaire) and specific network characteristics. Theoretical prediction on efficiency of specific structures are not confirmed. Subjects tend to overinvest especially in asymmetric network structures, while we observe more free riding in dense and symmetric structures like the full network or the overlapping neighbors structure. Predictions on the stability of specific equilibria are also not confirmed. Coordination fails in the dynamic setting and we do not observe any convergence of behavior towards a theoretically predicted equilibrium.

## Appendix A1

# Instructions

Thank you for participating in this research project. Your earning depends on your decisions and the decisions of the other participants. From now on until the end of the experiment you are not allowed to communicate with each other. If you have some question, raise your the hand and one of the instructors will answer the question in private. Please, do not ask aloud. Thank you very much.

The rules are equal for all the participants.

The project consists of 2 phases. The first phase consists of 34 situations. Each situation is independent of the other. In each situation you have to make a decision. Your payment at the end depends on these decisions.

In the second phase we ask you to fill out a questionnaire.

## Phase I (The Experiment)

In the first phase you will be in a sequence of "situations". Each situation is represented by a specific network structure that will be shown to you.

**1. In the first part** of this experiment you will be in the **same network structure for 4 periods**. In each period you will be asked to make a decision. After 4 periods you will be asked to look at the next network structure. Altogether, you will be in **five different network structures** and you will have to make **20 decisions**.

Each period you will be randomly assigned to a different position in a specific network. All other positions in that network will also have randomly assigned participants out of this room. Hence, each period you will be playing with **different participants** and **in a different position** in the network.

After this first part we will announce the beginning of the following second part:

**2. In the second part** of this experiment you will be in the **same network structure for 7 periods**. After 7 periods you will be asked to look at the next network structure. Altogether, you will be in **two different network structures** and you will have to make **14 decisions**.

Now you will keep the same network position over all 7 periods played in a network structure. **All other members** of that network will also not change their identity and positions in the network. Hence, each period you will be playing with the **same participants** which remain **in the same position** in the network.

The procedure for all 34 periods and all situations/networks is the following:

1. On the computer screen you will be asked to look at a network structure with a specific number, which you will find in the handout. You will also see on the computer screen which player (node number) you are in that network. Look carefully at the entire network structure!
2. Each player can produce know-how. You have to decide how much "effort" to invest into to the production of "know-how". For this you have to type in your "effort" as any number between 0 and 1, e.g. 0,1 or 0,25 or 0,3 or 0,33 or 0,5 or 0,75, or 0,8...etc. up to 1.
3. IMPORTANT: Your know-how is available to your direct neighbors, and the know-how of your direct neighbors will be available to you. Your direct neighbors are players with a direct link to you. On the basis of this total know-how (yours and your direct neighbors') your and your neighbors' payoff is calculated.
4. Thus, the net payoff that you can receive from "know-how" production in each period depends not only on your own effort but also on the effort of your direct neighbors. Please have a look at Table 1 (net payoff matrix) to see how the payoff changes with the effort decisions of

yourself and your direct neighbors. The values in the table correspond to Euros.

**Payment:**
At the end of the experiment, 3 out of the 34 periods are randomly chosen to determine your actual payment in Euros. Your actual payment will be the average payoff of these three periods picked. Additionally, you will get 5 Euros as a show-up fee.

All information which leads to the calculation of your payment will be made transparent.

## Phase II (The Questionnaire)

In the second phase we ask you to fill in a questionnaire. The personal data will be treated confidential and are only used for research. To prove our spending in case of investigation, we must ask you for your name and address. These data will be stored separately from the others.

Once you completed the questionnaire, we pay you the amount that you earned in the experiment, including the show-up fee of 5 Euro.

To make sure that everybody understands the rules of the game, we ask you some questions about the game.

## Quiz

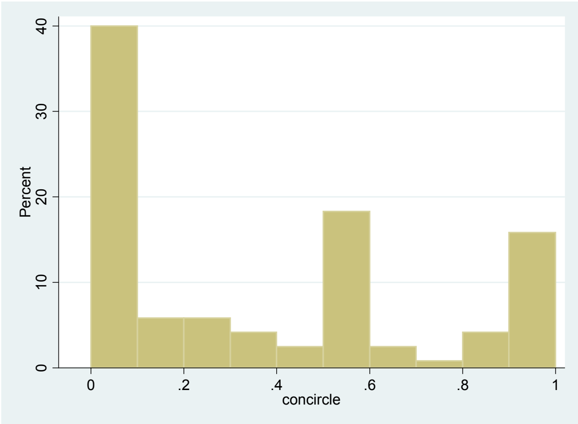
Before the experiment started, subjects had to answer a few questions concerning the rules.

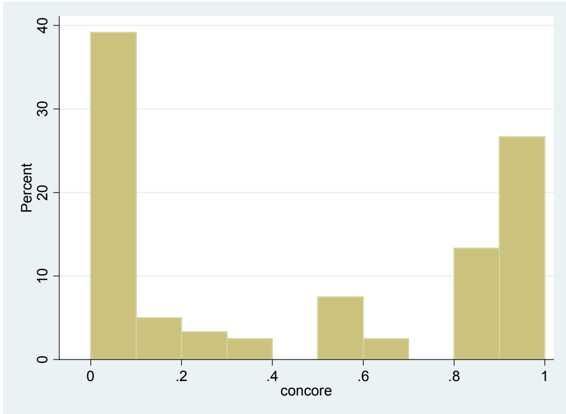
## Appendix A2

Payoff matrix in the hand out for the experiment:

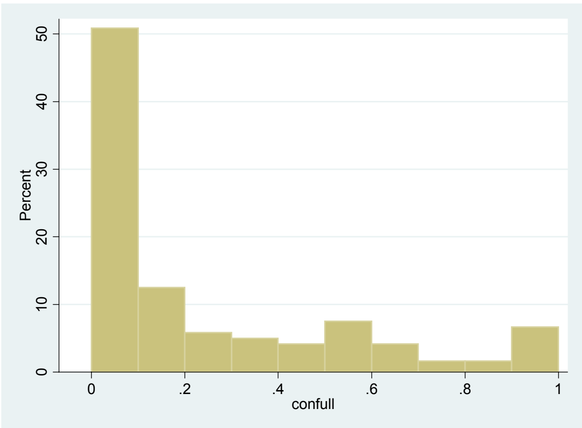
| Sum of your neighbours' effort (players that have a direct link to you) | Your own effort 0,00 | 0,10 | 0,20 | 0,30 | 0,40 | 0,50 | 0,60 | 0,70 | 0,80 | 0,90 | 1,00 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **0,00** | 0,00 | 0,34 | 0,62 | 0,84 | 1,02 | 1,17 | 1,28 | 1,35 | 1,41 | 1,44 | **1,45** |
| **0,10** | 0,71 | 0,99 | 1,22 | 1,40 | 1,54 | 1,65 | 1,73 | 1,78 | 1,81 | **1,82** | 1,81 |
| **0,20** | 1,37 | 1,59 | 1,77 | 1,92 | 2,03 | 2,10 | 2,16 | 2,19 | **2,20** | 2,19 | 2,16 |
| **0,30** | 1,97 | 2,15 | 2,29 | 2,40 | 2,48 | 2,53 | 2,56 | **2,57** | 2,56 | 2,54 | 2,50 |
| **0,40** | 2,52 | 2,67 | 2,78 | 2,85 | 2,91 | 2,94 | **2,95** | 2,94 | 2,91 | 2,87 | 2,82 |
| **0,50** | 3,04 | 3,15 | 3,23 | 3,28 | 3,31 | **3,32** | 3,31 | 3,29 | 3,25 | 3,19 | 3,12 |
| **0,60** | 3,53 | 3,60 | 3,66 | 3,69 | **3,70** | 3,69 | 3,66 | 3,62 | 3,57 | 3,50 | 3,42 |
| **0,70** | 3,98 | 4,03 | 4,06 | **4,07** | 4,06 | 4,04 | 4,00 | 3,94 | 3,87 | 3,79 | 3,70 |
| **0,80** | 4,41 | 4,44 | **4,45** | 4,44 | 4,41 | 4,37 | 4,32 | 4,25 | 4,17 | 4,07 | 3,97 |
| **0,90** | 4,81 | **4,82** | 4,81 | 4,79 | 4,75 | 4,69 | 4,62 | 4,54 | 4,45 | 4,35 | 4,24 |
| **1,00** | **5,20** | 5,19 | 5,16 | 5,12 | 5,07 | 5,00 | 4,92 | 4,82 | 4,72 | 4,61 | 4,49 |
| **2,00** | **8,24** | 8,11 | 7,97 | 7,83 | 7,68 | 7,52 | 7,36 | 7,19 | 7,01 | 6,83 | 6,65 |
| **3,00** | **10,40** | 10,21 | 10,01 | 9,81 | 9,61 | 9,41 | 9,20 | 8,98 | 8,76 | 8,54 | 8,32 |
| **4,00** | **12,07** | 11,84 | 11,61 | 11,38 | 11,15 | 10,91 | 10,67 | 10,43 | 10,18 | 9,94 | 9,69 |
| **5,00** | **13,44** | 13,19 | 12,93 | 12,68 | 12,42 | 12,16 | 11,90 | 11,64 | 11,38 | 11,11 | 10,84 |

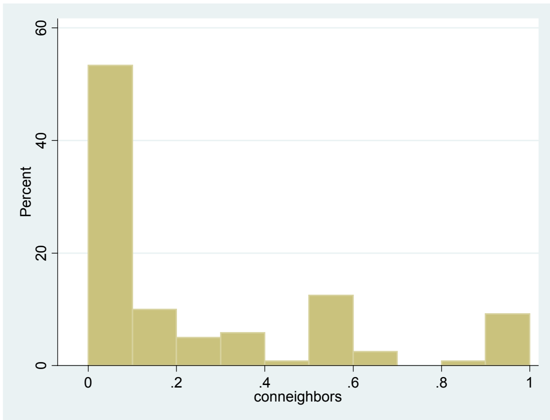
## Appendix A3



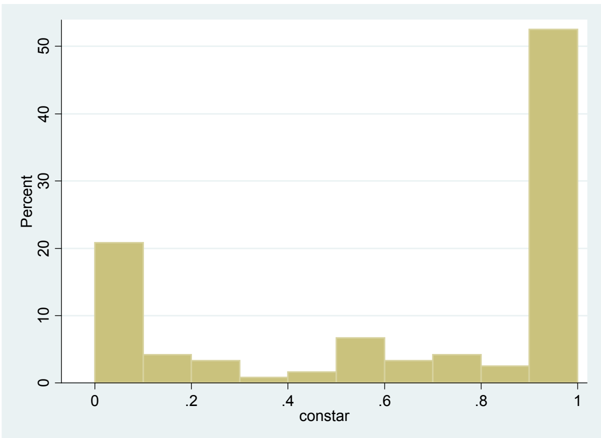




Investments in the circle and the core-periphery network




Investments in the complete and the overlapping neighbors network




Investments in the star network

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